Full Field Dishing Metrology for Hybrid Bonding Process

Matthieu PÂQUES, Wolfgang IFF, Anindita SAHOO, Thibault IMBERT, Clémence CHAUVET, Hadrien VERGNET, Vartika BANSAL, Dorra SOLTANI, Angela ALVAREZ, Mael WINTER, Michael SCHOEBITZ, Jean-François BOULANGER, Alain COURTEVILLE, Dario ALLIATA, Hugo BIARD*

Metrology & Inspection business of Unity Semiconductor SAS, Saint-Ismier, France, an affiliate of Merck KGaA, Darmstadt, Germany

*Corresponding author: hugo.biard@emdgroup.com

Abstract

Hybrid bonding requires tight copper dishing control to ensure both intimate dielectric-to-dielectric contact during bonding and reliable copper-to-copper electrical interconnection after annealing. Existing metrology methods present trade-offs: AFM provides accurate local references but limited throughput and field of view; OCD remains mainly statistical, and classical WLI is affected by transparent layers and material-dependent phase offsets. We introduce FDM™, a machine-learning-assisted optical interferometric method calibrated against AFM, enabling non-contact, full-field copper dishing metrology on heterogeneous hybrid-bonding surfaces for production monitoring.

Key words

Hybrid Bonding Interconnect (HBI), Hybrid Copper Bonding (HCB), Direct Bond Interconnect (DBI), Heterogeneous integration, Copper dishing, Machine Learning.

I. Introduction

Hybrid bonding is an enabling technology which has emerged in the last two decades, allowing industry to actively stack different wafers or dies through metallic contacts surrounded by dielectric [1].

Its applications lie in the framework of heterogeneous integration, where logic, memory, and pixel are built separately, with appropriate nodes and processes, before being assembled.

The first application was to enable high density interconnection for CIS (CMOS Image Sensor) between the pixel and the logic wafers, and higher pixel density. It is now entering into adoption for HPC (High-Performance Computing) for AI (Artificial Intelligence) for stacked memory, logic, and combinations of the latter (e.g. 3D NAND, HBF, 3D DRAM, HBM). In all those cases, interconnection latencies and aspect ratio need to be reduced as much as possible, and interconnection densified as much as possible [1].

In the last 20 years, different hybrid bonding (HBI) approaches have been tested, such as the early path requiring compressive force [2], the DBI (Direct Bond Interconnect) approach with Cu-SiO_2 materials [3] more widely adopted, and more recently the Cu-SiCN materials from IMEC [4].

In the hybrid bonding process, it has been highlighted that a key parameter to control is the Copper dishing value, that is the recess level of copper pads relative to the surrounding dielectric. In fact, due to the CTE (Coefficient of Thermal Expansion) mismatch between dielectric and Copper, the latter must be slightly in recess before the anneal step, typically around 300°C to 400°C, taking place after the bonding and ensuring proper electric contact between the different sub-elements of the heterogeneous integration. Dishing value too small would lead to unperfect contact between the dielectric areas, while dishing value too large would not allow bonding between the Copper pads, and so the electrical connection. Thus, it is critical to control Copper dishing values both locally and across the full wafer.

It brings the question of metrology for hybrid bonding, both for R&D and mass production. So far, the main solution in use is AFM (Atomic Force Microscopy), able to measure surfaces agnostically of the surface material, and up to nanometer in lateral (XY) and vertical (Z) resolution. Even though new “fast-AFM” [5] has arrived on the market in the last years, it still suffers limitations in terms of FoV (Field of View) size, throughput, stability, and potential contamination. We could also quote the Optical Scatterometry (OCD - Optical Critical Dimensions) technology, but with the limitation of doing only statistical control. And of course, the classical White Light Interferometry (WLI) has also been in use, with the advantage of larger FoV size, but suffering its own

limitations. In case of transparent layers, if the thickness is smaller than half of the source coherence length, the trains of fringes of each layer's interface overlap, and traditional reconstruction algorithm based on envelope detection then fail to disentangle the contribution of each layer to the signal [6]. In case of heterogenous surfaces, a mix of semi-transparent dielectric area surrounding reflective metallic pads, as used for hybrid bonding, the difference of refractive index will induce a phase shift. The reconstruction topography will then present a material offset [7]. Thus, for classical WLI, the common solution is to metallically coat the wafer surface to resolve the interferometric signals; at the cost of being a destructive method.

It is in this framework that we have developed in the last decade a novel approach combining Machine Learning and adapted optical interferometric signals. Called FDM™, for Full-field Dishing Metrology, this technology is a feature assisted reconstruction method: features are extracted during a calibration (training) stage based on the matching of interferometric signals with reference such as AFM data. After this first calibration, the inference measurements in production only required interferometric signals. Thus, this technology combines the advantages of the two technologies: the non-contact and high throughput nature of optical measurement, with the capability to measure heterogeneous surfaces composed of reflective (metallic) and semi-transparent (dielectric) areas where AFM stands strong. FDM achieved a 50-to-200-fold higher throughput than AFM for the same surface area, with same level of capabilities.

Machine learning has become a major data-driven approach for extracting patterns, building predictive models, and improving decision-making from complex datasets [8]. In optical metrology and inspection, its adoption has accelerated over the last decade, enabling advanced signal interpretation, phase and topography reconstruction, error compensation, and more robust measurements on complex or heterogeneous surfaces [9].

In this paper, for the first time, we present a comparative analysis of cartographies obtained with AFM and FDM, as well as the extracted dishing values. Profiles will be depicted, as well as statistics to study the correlation between AFM and FDM data, including R^2 (coefficient of determination) values. These results are reliable regardless of the number of metal layers beneath the surface. Thus, we intend to demonstrate the robustness of our technology for hybrid bonding processes, already proven for CIS, 3D NAND, and logic use cases.

II. Methodology

To provide Copper dishing measurements, our metrology needs to be calibrated (training) using AFM and optical interferometric data from the same set of wafers, and from the same location. The training set of data should be representative of the future inference set of data.

The requirements on the AFM data are light, as only the quality of the AFM topographic measurements impacts the quality of the metrology at the inference step. AFM measurements are performed on a separate tool. There is no brand or model requirement for the AFM tool itself.

Full field interferometry measurements are performed with the same type of optical sensors that will be used for further inference measurement (R&D or mass production). Thus, the sensors are integrated into the TMAP-NST tool, a metrological platform designed to support process control in Advanced Packaging [10].

When both AFM and optical interferometry acquisitions are done, we move to training, or calibration stage, using the algorithms developed in the last decade by this company, taking advantage of both our expertise in Machine Learning and in optical data treatment. ML algorithms are run to map the optical signal to the AFM topography map, providing a model with an appropriate set of weight, with a recurring feedback loop with a part of the data set to adjust the latter. The model parameters are updated to reduce the reconstruction error until they converge to a minimum. At the inference stage, the model produces a confidence score to guarantee that the input optical signal is within the teaching validity range. In this paper, for obvious confidentiality reasons we will not go into deeper detail of the recipe itself, but we will rather focus on the inference results.

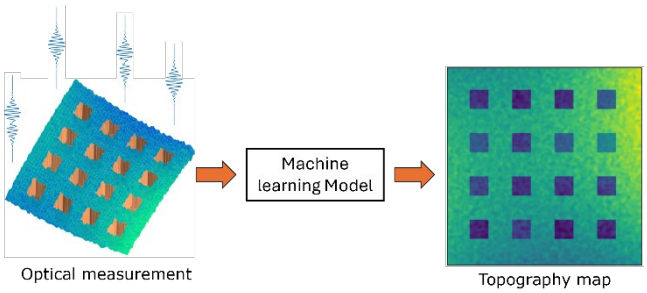


Fig.1 – Simplified illustrations of the FDM operating flow in inference mode.

Once the calibration is done, the model enables us to provide a topography, at the pixel level, on the whole FoV accessible by the optical interferometric acquisition. To test the resilience and capabilities of the teaching, tests are then performed using wafers of similar geometry, but which had not been used for the training step. Even if the beneath-surface (oxides and metals) layers must remain similar from teaching to inference, the in-plane geometry can change without impacting the accuracy of results. Otherwise, a new calibration is required.

The dishing values extracted on the test wafers are compared to the dishing values with the same pads obtained with AFM. Correlation quality is mainly assessed using R^2 values, both at the pad and FoV level. Examples of pad dishing visualization are also provided in this paper, both at FoV level and at wafer level.

The lateral optical resolution reachable with our FDM product is dependent on the resolution of the optical sensor. We have currently two versions: one being able to reach 1µm pad dishing capabilities, and a more advanced version to access sub-micrometer resolution.

III. Results

In the following, we present results obtained on several use cases. For confidentiality reasons, the name and exact application, as well as the exact critical dimension, are not disclosed. However, we will provide example of various size, from pad Critical Dimension (CD) of few micrometer sizes, to below 0.5µm one, and with HBI application ranging from CIS to Memory.

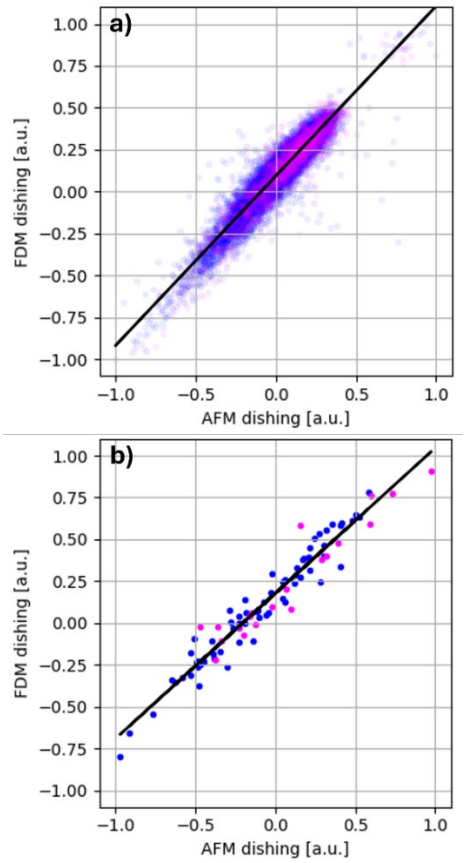


Fig.2 - AFM vs FDM pad dishing correlation per pad (a) and average per FOV (b). Black line from linear regression. Pink dots are validation data (not seen during training); and the blue dots are training data.

In Fig 2.a and 2.b, we present the correlation between the dishing values extracted with a standard AFM and our FDM sensor. In Figure 2.a, each point represents the value of an individual dishing value, while in 2.b, each point represents the dishing value average for an entire FoV. In both cases, the blue dots are associated with the training phase, while the pink dots are associated with the inference phase.

To judge the quality of the correlation between the AFM and the FDM dishing values, the main metric used is the R^2 value. For the cases in Fig 2.a and 2.b, we obtain respectively 0.88 and 0.94 for the individual pad and FoV correlation; that is above the R^2=0.8 value often used as quality threshold value. Furthermore, the corresponding linear regressions slopes are 0.80 and 0.87. Those values prove a highly accurate correlation between the AFM, considered as the reference tool, and FDM. We can also observe the absence of bias in favor of the training data as compared to the validation data.

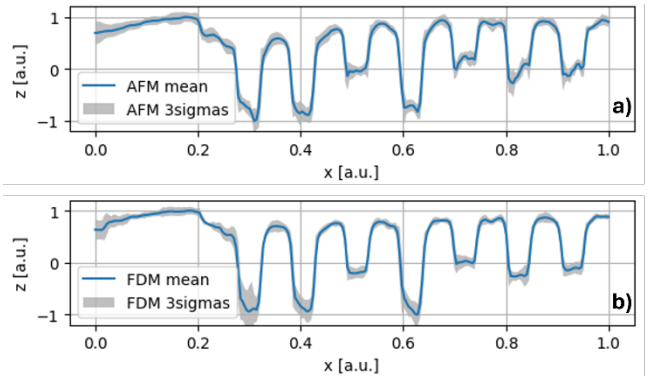


Fig.3 – In order to evaluate AFM (a) vs FDM (b) 3σ repeatability, 10 profiles were measured, with an extraction of 3σ values.

To evaluate the repeatability of our metrology sensor, we have performed the same measurement 10 times, with both AFM and FDM, on several pads. The profiles are presented in Fig.3, with the Copper pads being in depression and the TEOS in protrusion. 3σ values encompass both sensor dispersion, stability, but also the alignment and model stability for FDM. 3σ repeatability was 18% lower for FDM as compared to AFM. Thus, we can observe similar repeatability values, comforting the observation that the FDM metrology quality is linked to the one of the AFM used for the training of the model, and can even get free from AFM artifact.

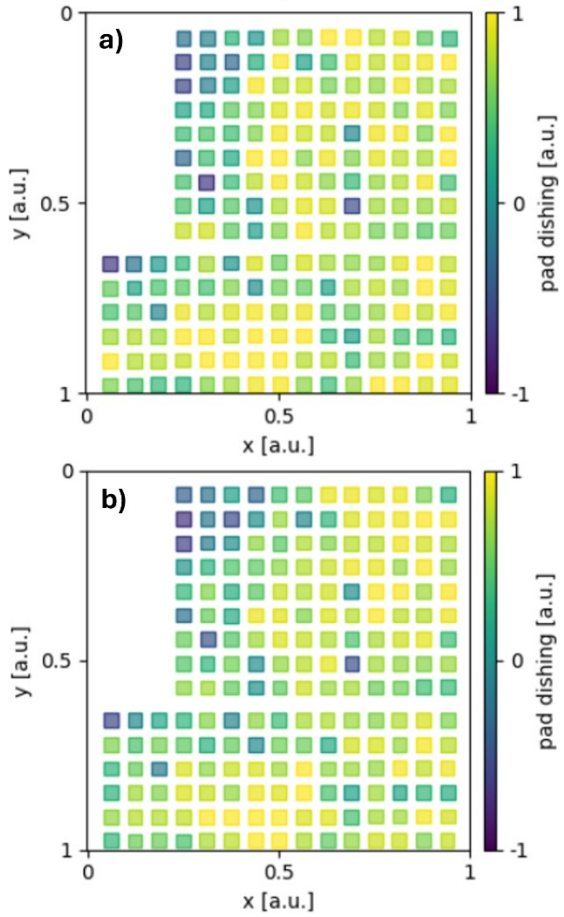


Fig.4 – Example of an array of pad dishing measurements at the FoV level, for both AFM (a) and FDM (b). Original FoV size is cropped to match a pertinent area.

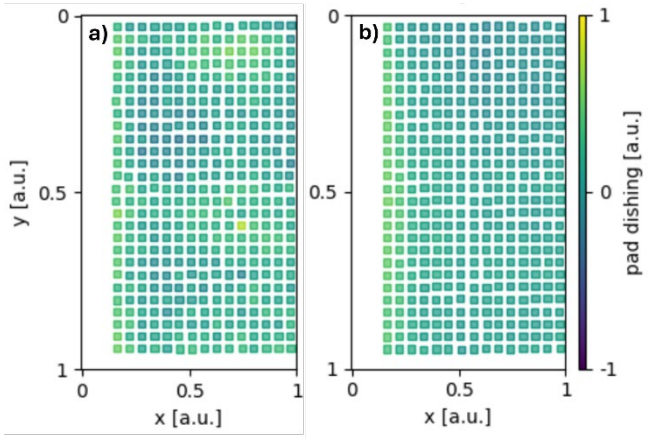


Fig.5 – Example of an array of pad dishing measurements at the FoV level, for both AFM (a) and FDM (b). Original FoV size is cropped to match a pertinent area.

As said, the FDM can perform measurements with the throughput of an optical interferometer, and for each FoV, extract a topography with a vertical accuracy of 0.1nm. It allows to extract precious information for hybrid bonding post-CMP processes, both at a local level, Field of View area, and macro level, wafer scale. In the following, we propose visualizing such information at both local and macro levels.

For two different use-cases, presented in Fig.4 and Fig.5, we propose a way to visualize the pad topography, with the color scale representing the dishing value. In both cases, the AFM (Fig. 4.a and 5.a) and FDM (Fig. 4.b and 5.b) extracted topography are compared. FDM std area size is 180x180µm², but is here cropped to match the AFM size, to ease the comparison. While scales are normalized for confidentiality, Fig.4 corresponds to around 3µm pad size, while Fig.5 corresponds to micrometer size pad.

In both cases, we can observe variation at the micrometer scale, meaning from one pad to another; and for example, higher dishing values at the interface between the pad array and the TEOS area. Being able to observe those effects at a local level is useful to link CMP parameters to pad dishing uniformity.

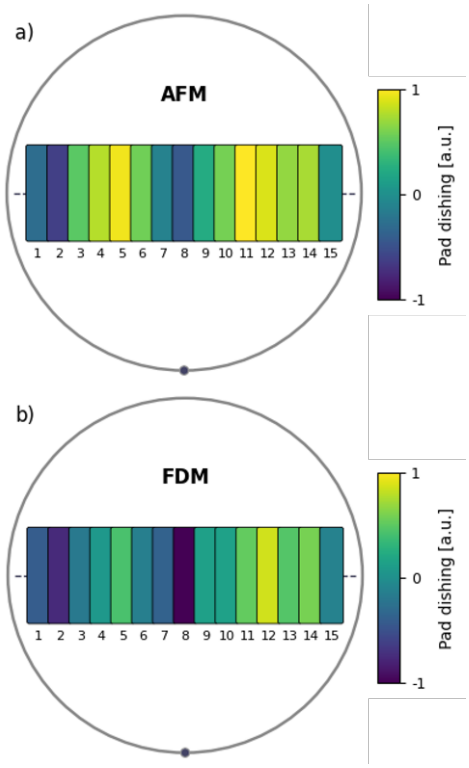


Fig.6 – Example of an array of pad dishing measurements along the wafer diameter, for both AFM (a) and FDM (b).

The optical nature of FDM, coupled with the FoV size, and the usual location automation, enables to analyses the features at the wafer level, and it is thus possible to quantitatively assess the effects of CMP and other process parameters at a macro scale, giving precious information for both R&D and mass production process control and optimization.

To ease interpretation, we present in Fig.6 the average dishing per FoV for all the dies on one wafer, for both AFM

(a) and FDM (b). In this case, we can observe an M shape, with lower dishing on the edges and the center of the wafer. Minor differences are noted between AFM and FDM profiles, mostly explained by the larger FoV size of the latter, and so average is made on a wider source of information. We have often seen such M shape structures. As well as V-shape, or more asymmetric or complexes ones. Those indications are stressed out as instructive by customers to tailor their pre-bonding process parameters.

IV. Conclusion

The industry is moving from TCB to Hybrid Bonding for a wide range of applications, with copper pad pitch decreasing, making the post CMP and pre-bonding inspection more critical than ever.

In this paper, we demonstrated the effectiveness of the FDM sensor to measure copper dishing on a heterogeneous surface, defined here as a mix of metallic reflective area, and dielectric semi-reflective area. After the calibration step using AFM, the FDM sensor can extract topographic measurements with only optical interferometric data. Thus, taking advantage of both the throughput and non-contact nature of optical interferometric measurements, as well as its 0.1nm vertical accuracy and large FoV. With access to both individual copper pad dishing values, as well as more macro level process control.

Additionally, as the FDM is calibrated at the pixel level, it is not subject to frequent artifacts observed with AFM, for example linked to piezo control or cantilever aging or also dust contamination, as well as complex post processing imaging.

With AFM to FDM correlation, and the associated R^2 values, we show the good matching between those two technics. The repeatability measurements presented in this paper also showed equivalent 3σ values, critical when it comes to the setting of CMP processes.

For all those reasons, we believe FDM is an exciting opportunity to complete the available metrological system used by the semiconductor industry.

Acknowledgment

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